Improved Bounds on Violation of the Strong Equivalence Principle

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Abstract. I describe a unique, 20-year-long timing program for the binary pulsar B0655+64, the stalwart control experiment for measurements of gravitational radiation damping in relativistic neutron-star binaries. Observed limits on evolution of the B0655+64 orbit provide new bounds on the existence of dipolar gravitational radiation, and hence on violation of the Strong Equivalence Principle.

1. Introduction

PSR B0655+64, in a highly circular one-day orbit with a ~ 0.8 $M_\odot$ white-dwarf companion, serves as a control experiment for measurements of orbital decay in the highly relativistic double-neutron-star binaries: General Relativity (GR) has predicted equally well the strong back-reaction to gravitational radiation for PSRs B1913+16 (Taylor 1993; see also Weisberg & Taylor, this volume) and B1534+12 (Stairs et al. 1998), and the absence of detectable orbital evolution for PSR B0655+64 over two decades. The long-term stability of the B0655+64 orbit sets unique bounds on departures from GR that give rise to dipolar gravitational radiation (Arzoumanian 1995, Goldman 1992), the existence of which would represent a violation of the Strong Equivalence Principle (SEP), one of the basic tenets of GR. Gérard & Wiaux (2002) examine the theoretical basis for dipolar gravitational radiation and suggest that bounds from binary pulsars may be competitive with future satellite experiments dedicated to probing SEP violation.

A definitive analysis of the available data for PSR B0655+64, and implications for a variety of alternative theories of gravitation, will be published separately (Arzoumanian et al. 2003, in preparation). Following recent observations to extend our long-term monitoring program, I present here preliminary results on the orbital evolution of PSR B0655+64.

1.1. Binary Pulsars and the Strong Equivalence Principle

The Strong Equivalence Principle posits that the response of a body to an external gravitational field is independent of the gravitational self-energy of the body; it would be violated if, for example, two objects with different gravitational binding energies were observed to fall at different rates. SEP is satisfied by postulate within GR; as a consequence, the lowest allowed multipole order of gravitational radiation is the "electric" quadrupole. If SEP does not hold,

however, emission of dipolar gravitational radiation is allowed, and lends itself in principle to indirect detection through decay of a binary orbit at a rate inconsistent with the quadrupole-order prediction of GR. Because self-gravitational effects are important in neutron stars, SEP can be tested with pulsar systems.

The most thoroughly studied theory of gravitation that violates SEP, the so-called "Brans-Dicke" scalar-tensor theory (Brans & Dicke 1961), invokes the existence of a scalar gravitational field that couples to matter through a single dimensionless parameter, ω_{BD}. The Brans-Dicke theory becomes indistinguishable from GR as ω_{BD} becomes arbitrarily large; solar-system experiments currently place a lower bound $\omega_{BD} \gtrsim 500$. Other alternatives to GR are also constrained by limits on dipolar gravitational radiation (see, e.g., Damour & Esposito-Farèse 1992): recent observations of distant type Ia supernovae suggesting that the expansion of the universe is accelerating have prompted renewed interest in theories involving scalar fields (e.g., "quintessence," Caldwell et al. 1998) or long-range forces that may be responsible for the acceleration. Such fields would radiate predominantly at dipole order.

The various contributions to observed changes in the orbital period P_b of a binary system (neglecting tidal and mass-transfer effects) can be expressed as

$$\left(\frac{\dot{P}_b}{P_b}\right)_{\text{obs}} = \left(\frac{\dot{P}_b}{P_b}\right)_Q + \left(\frac{\dot{P}_b}{P_b}\right)_D + \left(\frac{\dot{P}_b}{P_b}\right)_{\dot{G}} + \left(\frac{\dot{P}_b}{P_b}\right)_{\text{a}}, \qquad (1)$$

where the subscripts Q, D, $\dot{G}$, and **a** denote the effects of quadrupolar and dipolar gravitational radiation, a change in the gravitational constant with time, and the varying Doppler shift from a relative acceleration of the solar system and pulsar binary[1]. In a large class of metric theories of gravitation, the radiation terms for a circular orbit are given by (Eardley 1975, Will 1981, Goldman 1992)

$$\left(\frac{\dot{P}_b}{P_b}\right)_Q = -\frac{96}{5}\mathcal{G}^{-4/3}\left(\frac{\kappa_1}{12}\right)n^{8/3}m_1m_2M^{-1/3}T_\odot^{5/3} \qquad (2)$$

$$\left(\frac{\dot{P}_b}{P_b}\right)_D = -\kappa_D\mathcal{G}^{-2}(s_1-s_2)^2n^2\frac{m_1m_2}{M}T_\odot, \qquad (3)$$

where $n \equiv 2\pi/P_b$, m_1 and m_2 are the pulsar and companion masses in solar units, $M \equiv m_1+m_2$, and $T_\odot$ is the mass of the Sun in units of time. The dimensionless parameters κ_1, κ_D, and $\mathcal{G}$ describe the strength of quadrupolar and dipolar radiation and the effective gravitational constant in a given theory. In GR, $\kappa_1 = 12$, $\kappa_D = 0$, and $\mathcal{G} = 1$; in the Brans-Dicke theory, $\kappa_D\mathcal{G}^{-2} = 2(2+\omega_{BD})^{-1}$. At the level of the current constraint on the dipole term D, the $\dot{G}$ contribution to $\dot{P}_b$ in Eq. 1 can be neglected (Arzoumanian 1995, Kaspi et al. 1994).

The quantities s_1 and s_2 in Eq. 3 represent the "sensitivities" of the orbiting objects, the fractional change in binding energy of each star with G,

$$s = -\left(\frac{\partial \ln m}{\partial \ln G}\right)_N, \qquad (4)$$

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[1]To correct for Galactic accelerations and the "Shklovskii" effect, I follow Damour & Taylor (1991), using a new proper-motion measurement for B0655+64: $\mu = 6.8 \pm 1.1$ mas yr^{-1}.

where N is the total number of baryons. The sensitivity of white dwarfs is negligible; neutron stars are thought to have sensitivities in the range $0.15 < s < 0.40$ (Will & Zaglauer 1989), with larger values corresponding to "softer" equations of state. Results of X-ray burst oscillation modeling (e.g., Nath et al. 2002), and the recent detection of atmospheric absorption lines from a neutron star (Cottam et al. 2002), suggest that fairly stiff equations of state are appropriate. I therefore adopt a fiducial value $s = 0.2$ below. It is worth noting that the difference $(s_1 - s_2)^2$ in Eq. 3 strongly suppresses dipolar radiation from NS-NS binaries like B1913+16, so that the celebrated agreement of the latter's orbital decay rate with the GR prediction does not usefully constrain the existence of gravitational radiation at dipole order. In scalar-tensor theories, gravitational binding energy takes on the role of an effective gravitational "charge." Neutron star-white dwarf (NS-WD) binaries can therefore be expected to copiously emit dipolar radiation, if such radiation exists, because of the large difference in gravitational self-energy between the component stars.

1.2. PSR B0655+64

PSR B0655+64 was discovered during a survey of the Northern sky made with the NRAO 300 Foot telescope (Damashek et al. 1982). Timing observations began soon thereafter, and the companion was optically identified as a massive white dwarf by Kulkarni (1986). If we assume pulsar and companion masses of 1.4 $M_\odot$ and 0.8 $M_\odot$, Eq. 2 predicts a rate of orbital decay within GR, $\dot{P}_b^{\rm GR} = -2 \times 10^{-14}$, corresponding to a decay timescale for the orbit of $\tau_Q \sim 150$ Gyr.

2. Observations and Results

The current data span 20 years, including observations made with the NRAO Green Bank 300 Foot (Taylor & Dewey 1988), 140 Foot (Backus et al. 1982, Arzoumanian et al. 1994b), and GBT telescopes, as well as the NRAO VLA (Thorsett 1991) and Jodrell Bank Lovell (Jones & Lyne 1988) telescopes. We carried out intensive observing campaigns, to obtain good coverage of all orbital phases at a single epoch, every few years with the 140 Foot and recently with the GBT, and these data provide the interesting constraints on orbital evolution.

Pulse times-of-arrival (TOAs) were derived from observations following standard procedures and analyzed with the TEMPO software package, using the ELL1 binary timing formula (Lange et al. 2001). A least-squares fit of the entire dataset for rotational, astrometric, and orbital parameters produces residuals consistent with statistical fluctuations.

Orbital phase residual and period measurements over time are shown in Figure 1. The constancy of P_b confirms the result of the global timing solution: the available data bound changes in orbital period at the level $|\dot{P}_b|_{\rm obs} < 1.5 \times 10^{-13}$ (1σ), a limit ~ 7 times the GR prediction. Accounting for a small correction for relative acceleration (Eq. 1), we then have a 2σ upper limit on orbital evolution,

$$\left|\frac{\dot{P}_b}{P_b}\right|_{\rm obs} < 1.0 \times 10^{-10}\,{\rm yr}^{-1} \ (2\sigma). \tag{5}$$
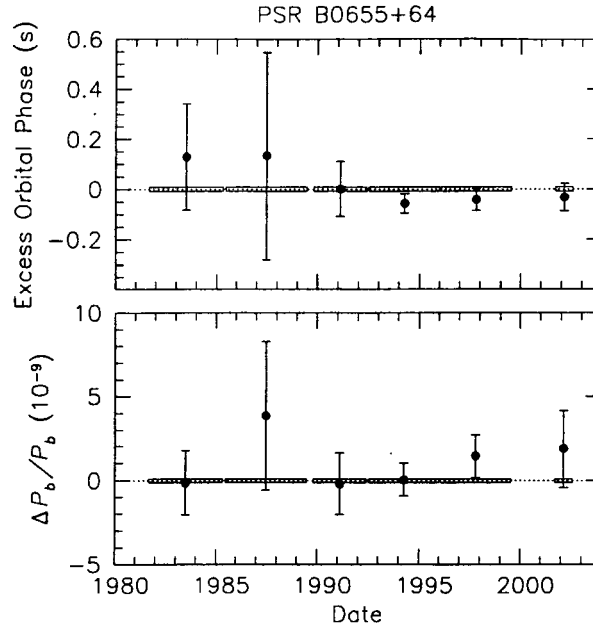
Figure 1.   Orbital evolution of PSR B0655+64. Box outlines depict ranges of dates over which phase and period measurements were made.

The resulting constraints on ω_{BD} are summarized in Fig. 2. Horizontal lines depict the current 1σ and 2σ limits on orbital decay in the PSR B0655+64 system. The curving dashed and dotted lines are the expected orbital period changes due to emission of gravitational radiation through quadrupole order, Eqs. 2–3, for NS sensitivities from soft and stiff equations of state respectively. The three curves in each set represent the (m_1, m_2) pairs (1.30, 0.7), (1.35, 0.8), and (1.40, 0.9), so that total system mass increases to the upper left. Constraints on ω_{BD} then lie at the intersections of the dashed or dotted curves with the measured upper limits on $\dot{P}_b$. From Eqs. 2, 3, and 5, we have in general

$$\kappa_D \mathcal{G}^{-2} < 0.006 \left(\frac{s}{0.2}\right)^{-2} \quad (2\sigma), \tag{6}$$

and for the Brans-Dicke theory specifically, $\omega_{BD} \gtrsim 320\,(s/0.2)^2 \ (2\sigma)$.

3.   Discussion

Prospects for improving bounds on SEP violation and the existence of dipolar gravitational radiation are good. Damour & Taylor (1992) show that, for constant data quality, measurement uncertainty for $\dot{P}_b$ scales with data span T as $T^{-5/2}$; moreover, data quality typically improves with time through improved instrumentation. Also, pulsar surveys continue to discover NS-WD systems similar to B0655+64 but with shorter orbital periods and millisecond pulse periods. Their higher rates of gravitational energy release coupled with higher timing precision suggest that these systems will surpass B0655+64 as laboratories for
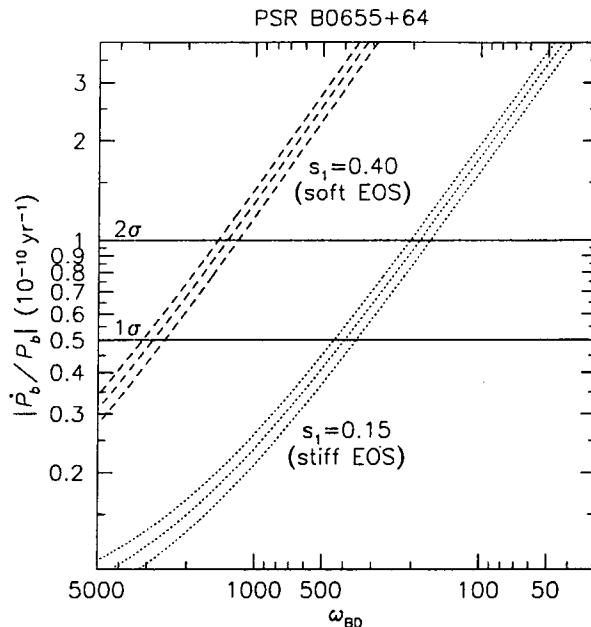
PSR B0655+64

Figure 2. Bounds on ω_{BD} from PSR B0655+64 (after Will & Za-glauer 1989).

testing theories of gravitation—Table 1 lists the current sample of relativistic NS-WD systems. While B0655+64 remains a valuable object of further study, a potential caveat applies to relativistic studies of all close NS-WD binaries: very small orbital separations can give rise to non-relativistic interactions. Heating of the companion star by irradiation from the pulsar is thought to power tides and mass loss in a handful of low-mass binaries. Outflows and tides cause significant orbital torques (e.g., Arzoumanian et al. 1994a), which would overwhelm any small secular trend due to gravitational radiation. If indeed the closest NS-WD binaries (e.g., PSR B0751+18; see Nice et al., this volume) are "clean" systems, significant new constraints on SETP violation will emerge in the coming years.

References

Arzoumanian, Z. 1995, PhD thesis, Princeton University

Arzoumanian, Z., Fruchter, A. S., & Taylor, J. H. 1994a, ApJ, 426, L85

Arzoumanian, Z., Nice, D. J., Taylor, J. H., & Thorsett, S. E. 1994b, ApJ, 422, 671

Backus, P. R., Taylor, J. H., & Damashek, M. 1982, ApJ, 255, L63

Table 1.   Relativistic NS-WD systems. Spin and orbital periods are shown alongside spin-down luminosity ($\dot{E}$), orbital separation (A) and timescales for orbital evolution from quadrupolar (τ_Q) and dipolar (τ_D) radiation. The potential for heating and tidal interactions between the component stars increases rapidly for increasing $\dot{E}$ and decreasing A.

PSR	P (ms)	P_b (d)	$\log(\dot{E}[\text{erg/s}])$	A (lt-s)	τ_Q (Gyr)	τ_D (Myr)
J1141$-$6545	393.9	0.20	33.4	4.5	2	2
J0751$+$1807	3.5	0.26	33.8	4.1	20	15
J1757$-$5322	8.9	0.45	33.2	6.4	20	15
B0655$+$64	195.6	1.03	30.6	11.3	150	60
J1012$+$5307	5.3	0.60	33.6	6.8	200	90
J1435$-$6100	9.3	1.35	33.1	14.2	250	90

Brans, C. & Dicke, R. H. 1961, Phys.Rev., 124, 925

Caldwell, R. R., Dave, R., & Steinhardt, P. J. 1998, Ap&SS, 261, 303

Cottam, J., Paerels, F., & Mendez, M. 2002, Nature, 420, 51

Damashek, M., Backus, P. R., Taylor, J. H., & Burkhardt, R. K. 1982, ApJ, 253, L57

Damour, T. & Esposito-Farèse, G. 1992, Classical Quantum Gravity, 9, 2093

Damour, T. & Taylor, J. H. 1991, ApJ, 366, 501

—. 1992, Phys.Rev.D, 45, 1840

Eardley, D. M. 1975, ApJ, 196, L59

Gérard, J.-M. & Wiaux, Y. 2002, Phys.Rev.D, 66, 24040

Goldman, I. 1992, ApJ, 390, 494

Jones, A. W. & Lyne, A. G. 1988, MNRAS, 232, 473

Kaspi, V. M., Taylor, J. H., & Ryba, M. 1994, ApJ, 428, 713

Kulkarni, S. R. 1986, ApJ, 306, L85

Lange, C., Camilo, F., Wex, N., Kramer, M., Backer, D. C., Lyne, A. G., & Doroshenko, O. 2001, MNRAS, 326, 274

Nath, N. R., Strohmayer, T. E., & Swank, J. H. 2002, ApJ, 564, 353

Stairs, I. H., Arzoumanian, Z., Camilo, F., Lyne, A. G., Nice, D. J., Taylor, J. H., Thorsett, S. E., & Wolszczan, A. 1998, ApJ, 505, 352

Taylor, J. H. 1993, Classical Quantum Gravity, 10, S167

Taylor, J. H. & Dewey, R. J. 1988, ApJ, 332, 770

Thorsett, S. E. 1991, PhD thesis, Princeton University

Will, C. M. 1981, Theory and Experiment in Gravitational Physics (Cambridge: Cambridge University Press)

Will, C. M. & Zaglauer, H. W. 1989, ApJ, 346, 366